Guidance for Optimizing Ground Water Response Actions at Department of Energy Sites

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INTRODUCTION

Purpose: The purpose of this guidance is to provide Environmental Restoration (ER) project managers and decision makers with an overview of key considerations in designing and implementing optimal ground water response strategies. The guidance outlines the typical phases of a ground water response and discusses important information needs to optimize technology applications for each phase. In those situations where restoration is determined not to be practicable, the guide outlines how the U.S. Environmental Protection Agency's (EPA) programmatic expectations for ground water can be used to establish measures that are necessary and appropriate to minimize risks to human health and the environment.

Background: Restoration of ground water contaminated from historical Department of Energy (DOE) activities poses a daunting task. Challenges arise as a result of difficult hydrogeologic settings (e.g., karst, fractured rock, extreme depth), recalcitrant contaminants (e.g., tritium, dense non aqueous phase liquids (DNAPL), technetium 99), and sheer volume of contaminated water. The significant resources that will be needed to address contaminated ground water make it imperative that the DOE ensure the most effective technologies are selected and their implementation optimized.

Currently, a significant portion of the DOE's ground water cleanup costs are associated with the operation of pump and treat systems, yet it has long been recognized that pump-and-treat remedies may not achieve restoration within a reasonable time frame in many settings typical at DOE sites.[1] Although effective in addressing higher levels of contaminant concentrations, once optimization measures (reconfiguration of extraction wells or screening intervals, alteration of pumping rates) have been fully utilized, continued operation of a pump-and-treat system is generally not cost-effective in addressing the more dilute portions of the remaining plume. Therefore, alternative approaches to pump and treat such as in-situ destruction technologies are generally favored if they will reduce the operating period for remediation or otherwise cut life-cycle project costs. However, these measures often have high initial implementation costs and may not always be cost-effective at a field scale in the more complex environments. If such aggressive front-end actions are not successful at significantly reducing the required period of performance of ground water remedies, they may add to the life-cycle cost, rather than reduce it. As a consequence, project managers must focus investigations and performance monitoring appropriately so the necessary data are available to make the attendant cost-benefit decisions for each technology application and phase of a response.

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[1] In a review of pump-and-treat remedies in the U.S., the National Research Council determined that at 69 of 77 sites studied, restoration had not been achieved to date and could take extended periods of performance for contaminant concentrations to be reduced below maximum contaminant levels (MCLs). (NRC, 1994)

DESIGNING OPTIMAL RESPONSE STRATEGIES

Planning Response Priorities

The EPA's goal is to restore ground water to its highest beneficial use regardless of whether the extant contamination poses an actual risk at the present time, i.e., the goal is to restore the resource, regardless of whether there is a current or projected demand for the water as a drinking water source.[1] In other words, ground water contamination is addressed under a "resource-based" approach. As a result, the initial field of remedial action objectives (RAO) is narrowed to restoration. However, the actual restoration of ground water is often a long-term proposition that may not address more immediate exposure concerns at a given site. Therefore, both risk and resource considerations are used to identify the optimal manner in which to respond to ground water contamination.

The EPA also recognizes that restoration may not always be practicable and therefore has developed a hierarchy of programmatic expectations that can be used to guide the establishment of alternate RAOs to restoration and associated response strategies:

- Restore ground water to highest beneficial use;
- Stop plume growth and migration of contaminants; and
- Reduce the toxicity, mobility or volume of contaminants.

[NOTE: Although the EPA's hierarchy is used to set ultimate response objectives and end states, a risk-based decision process for establishing the order in which activities are undertaken is required to ensure human health and the environment are fully protected. Therefore, this hierarchy does not necessarily parallel the sequence in which actions should be taken.**]**

Addressing Current or Imminent Risk

Since the order in which actions are taken should be determined on the basis of risk rather than the broader resource protection framework through which ultimate programmatic objectives are selected, the first and foremost consideration is whether any current or imminent exposures exist that need to be expeditiously addressed. In order to assess the latter, it is necessary to understand: 1) the magnitude and disposition of the plume as well as its trajectory; and 2) the location of potential receptors and likely exposure pathways. Hence, initial investigations must focus on outlining the general extent of the plume, the flow net of the affected aquifer, and the spatial distribution of potential receptors.

With regard to the <u>magnitude and disposition of the plume</u>, at a minimum it is necessary to obtain sufficient data to be able to map concentration isopleths, and in particular, the threshold isopleth (the concentration contour equivalent to the target cleanup level). Selection of the

[1] Most states also view ground water as a potential drinking water source and have set similar expectations for restoration whenever contaminants are present.

appropriate target concentration, however, first requires a determination of the current or highest beneficial use of the aquifer.

In general, it is assumed that the highest beneficial use will be as a supply of potable water unless insufficient yield or impaired quality renders the water unsuitable as a drinking water source. Federal guidelines for ground water classification suggest a minimum threshold yield of 150 gallons per day.[2] Many States have established their own minimum yield requirements for designation of an aquifer as a potable supply that differs from the federal guidelines, including some for which there is no minimum value. Therefore, State regulations must be reviewed on a site-specific basis to determine what criteria apply.

Aquifers that do not meet the minimum yield generally discharge to other aquifers or surface water bodies and would need to be evaluated on the basis of their impact on those receiving waters. In situations where discharge is to surface waters, ambient water quality criteria (AWQC) for the receiving water body likely will define the target cleanup criteria. Hence, critical data needs early in the investigation are an estimate of the yield of the affected unit to determine if it qualifies as a potable supply and the calculated flux to receiving waters, e.g., surface water bodies or other aquifer units.

In addition to insufficient yield, ground water units may not be considered potable supplies if naturally occurring conditions render it unsuitable for drinking. Brackish water (total dissolved solids concentrations greater than 10,000 mg/L) or the presence of toxic constituents, e.g., arsenic, is the most common conditions eliminating aquifers as drinking water sources. Therefore, a second early data need is to establish the quality of the affected ground water relative to its potential use as a water source. Characterization efforts to determine quality should be conducted in concert with efforts to map the threshold isopleth. The latter requires synoptic rounds of samples (preferably reflecting the extremes in the hydrologic cycle, i.e., wet and dry seasons) to provide at least two temporally equivalent sets of data for the entire plume.

In order to determine the <u>trajectory of the plume</u>, it is necessary to obtain sufficient data to develop the flow net for the area within and down-gradient of the threshold isopleth. Ultimately, these data can also be obtained as a part of the synoptic characterization work, but several preliminary rounds may be necessary to determine flow directions and assist in locating plume characterization wells.

Once the magnitude and trajectory of the plume are sufficiently understood, it is essential to identify all wells that may be used for potable purposes in the plume or its path. All wells identified within the threshold isopleth should be sampled. Similarly, potentially impacted wells outside the threshold isopleth but within the projected leading edge of the plume, should also be located and sampled to determine if unacceptable exposures are occurring. Wells in the path of the plume should be identified and targeted for periodic follow-on sampling to provide protection against future exposures should contaminants continue to migrate. In situations where a migrating plume is sufficiently close to drinking water extraction wells, plume containment may be necessary as an interim action until sufficient information is available to select a final

[2] *Guidelines for Ground-Water Classification under the [1984] EPA Ground-Water Protection Strategy*, Final Draft, November 1986.

ground water response strategy. Whenever wells are found to be compromised, the residents should be offered an alternate water supply or well-head treatment units to prevent unacceptable exposures from occurring.

If contaminated ground water discharges to surface water bodies, characterization of the receiving water is necessary to determine if there is an unacceptable risk to the environment. When such impacts are noted, the plume should be captured and treated to protect potential receptors. Primary concern is placed on discharges that exceed AWQC and potentially impact rare and endangered species, or entire communities/populations.

Ground Water Restoration Evaluation

Once provisions have been made to address a current or imminent risk, the focus shifts to the evaluation of viable measures for restoring contaminated ground water to its highest beneficial use. Generally, restoration is achieved in one of two ways: 1) sufficient contaminant mass is removed from, or immobilized in, the affected area to reduce soluble concentration levels below target criteria; or 2) sufficient contaminant mass is destroyed to reduce soluble concentrations below target criteria. Heterogeneity, isotropy, permeability, extraction potential and solubility determine our ability to remove contaminants from, or deliver reagents to, the matrix. In general, restoration is more easily accomplished in aquifers that are homogeneous, isotropic and highly conductive, and where contaminants are highly soluble, and readily extracted from water. Restoration becomes more difficult where heterogeneity, anisotropy, reduced permeability, reduced solubility, or increased difficulty of extraction or destruction exists. An example of a circumstance that poses a severe challenge to restoration is DNAPL in complex alluvium, fractured rock, or karst systems.

Typically, measures necessary to restore ground water consist of three principal phases: 1) a **source control phase** - in which remedial measures are used to eliminate the source(s) contributing contaminants to the subsurface; 2) a **mass removal/containment phase** - in which the higher level concentrations are removed/destroyed to effectively control contaminant migration and contribute to the containment or restoration of the plume;[3] and 3) a **monitoring phase** - in which (**a**) contaminant concentrations presumed to be at or below target criteria are monitored over a sufficient period of time for attainment of the cleanup criteria to be confirmed statistically, thus warranting termination of any access restrictions previously instituted to prevent exposure, <u>or</u> (**b**) low level concentrations - above the target criteria but below a level that can be cost-effectively addressed through engineered measures - are managed under a carefully controlled monitoring program until natural processes attenuate levels to the target criteria. **[NOTE**: The latter situation would constitute monitored natural attenuation (MNA) as the final phase.**]**

The key to designing an optimal response strategy is to clearly identify the specific objective for each technology/phase of the response, and to establish explicit criteria on when to transition between these technologies or phases. Equally important, decision makers need to determine how best to communicate the response plan to stakeholders to ensure they fully understand the

[3] In some situations, plume containment through engineered barriers at the periphery of a plume may be initiated prior to source control measures to address an imminent risk concern.

objectives for each phase, how performance in meeting these objectives will be measured, and how protection will be ensured in the event specific objectives are not fully realized. These key considerations are discussed in the following sections.

Evaluation of Source Control Measures

The source of ground water contamination represents the single most concentrated inventory of contaminant mass in the system. Subsequent release, transport, and attenuation serve only to dilute and reduce that inventory over time. Hence, to the extent it still exists, the most efficient place to reduce contaminant mass is at its primary source. Primary sources are typically identified as:

- Bulk materials in containers (buried drums, underground storage tanks);
- Waste repositories such as disposal cells;
- Concentrated residues in site soils; or
- Pure phase materials in the saturated zone.

The effort required to locate and address these source types varies significantly. Buried <u>containerized sources</u> are relatively easy to locate with geophysical survey techniques and physically remove. Similarly, <u>disposal cells</u> are generally easy to locate, however, the nature of the contents, their size or their geologic setting may render exhumation impracticable, thus warranting containment in place by installing caps or other barriers.

Locating <u>concentrated chemical residues</u> that are not containerized is typically accomplished through soil gas analysis or soil sampling, depending on the nature of the contaminant and the permeability of the soil. Similarly, contaminant and site characteristics will dictate which of the available technologies to address soil sources will be most effective. For **volatile** contaminants such as chlorinated solvents, soil vapor extraction is generally the preferred remedy in permeable soil, whereas excavation followed by thermal desorption or incineration typically are more effective with impermeable soils. The preferred remedy for **semi-volatile** contaminants generally is in situ or ex situ bioremediation when feasible. When bioremediation is not feasible, soils may be excavated and treated with either thermal desorption or incineration. In-situ chemical oxidation is emerging as an alternative means of destroying organic contaminants in place. The preferred remedy for **metals and radionuclides** is generally excavation followed by reclamation. However, reclamation often is not feasible and stabilization/immobilization of the contaminants in the soil matrix becomes the preferred approach. When contaminants are not amenable to stabilization/immobilization, residues may be contained in place with caps or excavated and transported to more suitable disposal sites.

<u>Pure phase sources</u> in the saturated zone are often extremely difficult to address. The most common form of these sources is DNAPL. These materials consist of low solubility liquids with a specific gravity greater than 1.0, e.g., trichloroethylene, creosote, and pentachlorophenol. As a result of their unique physical and chemical properties, these fluids flow down through the water table and lodge on low permeability surfaces. They are not greatly affected by convective currents produced by extraction wells and may move in directions other than that of the regional ground water flow. DNAPL can reside in large pools, but is more likely to be present as ganglia in small dendritic formations dictated by the structure of the pore space at the interface with less permeable strata. As a consequence, DNAPL deposits are difficult to locate. Some success has

been achieved with geophysical techniques applied to large deposits while innovative approaches such, as evaluating differential adsorption of tracers, is also under development. Rarely are DNAPL residues observed directly. More often, their presence is inferred from the patterns of chemical use (potential release of volumetric sources of pure liquid phase) and observation of indicative contaminant patterns (increasing concentrations with depth in the saturated zone beneath the release site and ground water concentrations in excess of one percent of saturated solubility).

When sources are present in the saturated zone, they are difficult to control. Recent developments with thermal recovery (six-phase heating; dynamic underground steam stripping) and in-situ chemical oxidation using Fenton's reagent or permanganate solutions show promise, but under certain site-specific conditions they still may not be capable of attaining a sufficiently high degree of removal to result in a truly meaningful reduction in risk or the time required for restoration of ground water to target concentrations for these chemicals (often in the range of parts per billion). Furthermore, the difficulty in finding and quantifying DNAPL mass also makes it difficult to determine the percentage of mass that is actually removed by one of these responses.

Given these considerations, investigations pursuant to source control should first focus on identifying the location and nature of sources and, if possible, their relative mass. When there is evidence of sources in the saturated zone, it is instructive to determine if there is a correlation between ground water concentration and storm events. If ground water concentrations in the source area increase with precipitation, unsaturated zone sources are likely significant. If storm events have no impact or a negative effect on ground water concentrations, saturated zone sources may be indicated. Saturated zone sources may be secondary sources associated with contaminant adsorbed on the aquifer matrix or concentrated residues such as DNAPLs.

Regardless of the type of source, once identified, it is necessary to determine the potential efficacy of source control measures. Aside from any risk posed by direct contact with soil sources, source control measures are of benefit if they can either significantly reduce the time required to restore the ground water (either the entire affected area or discrete portions thereof) to its highest beneficial use, or prevent as yet uncontaminated areas from becoming contaminated. The evaluation of such potential benefits requires an estimate of the flux of contaminants from the source into the ground water and the time frame over which the ground water in the area of interest will be restored. The former can be estimated from water balance calculations, flow rates, and concentrations. The latter requires a model of how concentrations will decline over time with no intervention, i.e., through natural processes alone, and how those rates of decline would be accelerated if an active remedy is implemented.

In its most simple form, the "no action" model may be a stochastic projection of concentration over time using existing temporal trend data. When monitoring data have been collected over a sufficient time frame under comparable conditions, they may indicate a trend along the lines of a first order decay curve. The apparent decay constant can be used to project concentrations in the future. However, caution is warranted as experience suggests that most mathematical models of restoration underestimate the time requirements because of their inability to properly account for heterogeneities. Although a smooth relationship may be indicated, it may be due to the combined effect of multiple phenomena and could be subject to changes in the future different than what would be predicted with simple straight line extrapolation. Hence, monitoring is needed to continually calibrate and verify the models being used to predict contaminant concentration trends over time. Site-specific circumstances ultimately will determine whether there is time to collect the temporal data necessary to substantiate concentration trends in a defensible manner. **[NOTE:** Generally, current or imminent risk should not be an issue at this phase of the analysis since such concerns should have been evaluated previously and addressed as necessary.**]**

If an estimate of source mass can be made, the calculated source flux rate can be used to similarly project mass depletion rates over time. By overlaying reasonable estimates of remedy effectiveness, it is possible to determine if source control is likely to be beneficial. Such an analysis will result in one of the following three conclusions:

- Unsaturated source will extend the time required for restoration and, therefore, source control should be pursued;
- Unsaturated source has dissipated to the point where it is too small to have a substantive, future impact on ground water and, hence, source control is not beneficial;[4] or
- Saturated zone source currently dictates plume dynamics and the benefit of control measures (and the degree to which they should be pursued) needs to be evaluated.

In the latter case, it may not be possible to predict effectiveness of available saturated zone source control measures with the desired level of accuracy. As an alternative, the approximate level of effectiveness required to be of benefit can be estimated and an evaluation made as to whether that level of effectiveness can reasonably be achieved given available technologies.

Regardless of the type of source being addressed and technology being applied, the key to ensuring a cost-effective response is to identify the point at which further source control cannot be achieved or will not be beneficial. Depending on the type of source control selected, termination may be based on design or performance criteria. If capping or other means of containment are used for source control, design criteria are applied. The source control phase is complete when the design has been installed and determined to be operational and functional. If removal or destruction of the source materials is the selected approach, performance criteria are applied. An example is the use of soil vapor trigger concentrations to determine when soil vapor extraction is no longer beneficial and can be halted.

When source control measures have been selected, the focus shifts to an evaluation of mass reduction within the plume as a means to contain the plume (if not done previously through peripheral control measures to address an imminent risk concern) and, where possible, to restore ground water.

Evaluation of Mass Reduction Measures

<u>Containment Assessment</u>: Plume containment is desirable as a means of minimizing the total volume of the ground water resource that is ultimately affected by contamination. If the plume is already static or retreating, additional measures to secure containment are not required. However, due to the slow travel times typically involved, stasis can be difficult to establish

[4] Source control still may be pursued if direct contact risks are of concern.

without a fairly lengthy observational period. Therefore, project managers should always determine the likelihood that stasis has been attained due to the lack of a continuing source or the presence of attenuating processes. When observational periods are relatively short, a greater level of analysis may be required to support the appropriate course of action.

If contaminants are still spreading, project managers need to determine if engineered barriers are needed or whether mass extraction/contaminant destruction in the higher concentration areas of the plume are most appropriate. If calculations show that stasis can be attained relatively quickly using a mass removal approach, and no significant risk concerns exist in the interim, mass removal may be preferable over engineered barriers as mass removal may significantly contribute to the ultimate restoration of the ground water. The decision between these options should be based on cost and risk considerations.

<u>Engineered containment</u> can be accomplished physically (sheet piling or slurry walls), biologically (phytoremediation), chemically (permeable treatment walls), or hydraulicly (pump and treat capture systems). In order to successfully install engineered containment, it is necessary to know the flow rates and stratigraphy at the site. Flow rates are critical for physical and hydraulic barriers since they define the rate at which water must be captured and the amounts that must be retained. With chemical and biological barriers, flow rates determine the dimensions of the barriers to ensure adequate contact time and/or uptake.

<u>Hydraulic containment</u> can be compromised when flow occurs through preferential conduits such as solution channels (karst) or fractures. Hydraulic barriers function best in high trasmissivity flow regimes that behave according to Darcy's Law.[5] Hence, investigations to support an evaluation of containment should include determination of permeability and connectivity between contaminated strata or zones.

The presence of impermeable layers may jeopardize the effectiveness of hydraulic and biological barriers by preventing access to impacted water, while their absence may render physical or chemical barriers ineffective because of the need to prevent underflow. Therefore, investigations should determine the presence and continuity of low permeability strata near the plume.

Containment can also be achieved by sufficiently <u>removing mass</u> from the plume (through pump and treat or destruction technologies) to reduce subsequent flux rates at the threshold isopleth to a level below the capacity of the prevailing attenuation mechanisms. When containment is sought through mass removal, the key to optimization lies in knowing the minimum removal that must be achieved. Therefore, project managers need a good estimate of attenuation capacity at the threshold isopleth pursuant to calculating the minimum removal required for containment through mass removal.

Once containment has been achieved, either through engineered measures at the plume boundary or mass reduction within the plume, the appropriateness of further mass reduction as a viable and cost-effective means for restoring the ground water needs to be evaluated.

[5] Velocity of flow through a porous medium is directly proportional to the hydraulic gradient (assuming flow is laminar and inertial forces can be neglected).

<u>Restoration Assessment</u>: Restoration of ground water is accomplished once contaminant concentrations are reduced to levels at or below those deemed safe when the water is put to its highest beneficial use. To evaluate the worth of additional mass reduction as a means to restore ground water, it is necessary to compare **a)** the time required to attain target criteria without additional measures being implemented against **b)** the time required to attain target criteria utilizing a proposed response technology(ies). Because source control and plume containment already will have been achieved, and any imminent risk concerns previously addressed, this comparison becomes, in essence, a cost-benefit analysis, i.e., to what extent is the time required to attain target criteria being reduced and at what projected cost. However, the decision on whether an active approach is cost-effective, and therefore should be pursued, will be a risk management decision based on additional site-specific considerations, e.g., future use needs of the ground water, the reliability of controls to limit access, etc. **[NOTE:** Even if restoration is determined to be technically impracticable (TI), in most situations restoration of some portion of affected waters will be possible. Mass reduction considerations under such circumstances are subsequently discussed in the TI section.**]**

Monitoring

As discussed earlier, the final phase of ground water restoration will always be a period of monitoring. In situations where site conditions and available technologies allowed a sufficient degree of effectiveness to reduce concentrations to target criteria, this phase will likely be a relatively brief period in which data are collected to ensure restoration can be statistically verified over time, or to ensure no rebound occurs when such a concern exists. In this situation, the final phase of the response can be viewed simply as a confirmation period used to provide decision makers with an adequate level of assurance that in fact access restrictions can safely be removed.

In those situations where site conditions and available technologies could not attain target criteria, or the analysis supported a conclusion that additional mass removal through active measures would not substantively expedite attainment of target criteria beyond what natural processes would alone, nor further reduce potential risks, this final phase would constitute an MNA approach. In these circumstances, the phases of the ground water restoration strategy would track the EPA's "favorable conditions" required to utilize MNA as a remedial option, i.e., the transitions between phases of the ground water response would occur as each precondition for application of an MNA remedy is met. The first phase used to address current or imminent risk is complete when the potential for near-term unacceptable exposures has been eliminated (favorable condition 1). The second phase, source control, is complete when no active source remains (favorable condition 2).[6] The third phase, containment, is complete when the plume is brought to equilibrium (favorable condition 3). Finally, the MNA phase is implemented when sufficient mass removal has occurred to be able to demonstrate that natural attenuation mechanisms will be able to restore ground waters within a time frame that is compatible with future use (favorable condition 4) and reasonable as compared to more active measures (favorable condition 5).

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[6] As defined in the DOE's previously issued MNA guides, an active source is *any inventory of contaminant in the environment that is being released to the plume at a rate greater than that at which it can be attenuated*, *i.e.*, *the inventory of mobile contaminants is increasing over time at a rate such that concentrations will exceed health-based levels*.

TECHNICAL IMPRACTICABILITY

As discussed earlier, the EPA recognizes that restoration of ground water within a reasonable time frame may not always be practicable.[7] Ultimately, the practicability of restoration will be a function of both the contaminant(s) and the aquifer matrix. Therefore, project managers will need to evaluate the nature and extent of the contamination and the aquifer matrix *to the extent necessary to predict the time required for candidate responses to achieve criteria concentration levels in the aquifer.* Essential data include estimates of contaminant inventory, pore water flushing times, partitioning, and connectivity. Important considerations with respect to currently available technologies are:

- Pump-and-treat systems will not extract DNAPL effectively
- Pump and treat will flush the permeable conduits while contaminant migration from less permeable zones will be diffusion limited and may sustain ppb range concentrations indefinitely
- The difficulty in locating DNAPL and the removal efficiencies required to address the rate-limiting fraction in the matrix hinder the ability of current technologies to reduce restoration times to less than 100 years
- If reagents are not significantly more mobile than contaminants, in situ approaches based on the introduction of chemicals will suffer the same limitations as pump and treat
- Passive remedies such as permeable treatment walls require the contaminants to come to them and therefore are constrained to natural flushing times

Given the above considerations and the low cleanup criteria associated with many contaminants, restoration may be impracticable more frequently than originally anticipated. However, a conclusion that restoration is impracticable is simply a recognition that currently available technologies are unable to achieve the desired goal in a reasonable time frame, and a different focus is needed to provide the necessary assurances that human health and the environment are adequately protected over time. This shift in focus to alternate RAOs may result in the consideration of similar technologies initially evaluated for the restoration RAO, but whose use (and system design) are now evaluated within the context of achieving a different objective. Furthermore, the implementation of remedial measures to meet these alternate RAOs may have already been initiated prior to making a TI determination. Ultimately, whatever measures are taken may lead to the eventual restoration of ground water, but the conclusion is that the time required to do so would not be considered reasonable.[8]

Limit Plume Growth and Contaminant Migration RAO

Containment is often more readily accomplished than restoration, however, even containment is <u>not</u> always assured. In aquifer matrices with poor connectivity such as fractured bedrock and

[7] Although the EPA has not explicitly established a limit on what constitutes a "reasonable time" for restoring ground water, several EPA Records of Decision have made findings of technical impracticability when restoration would require more than 100 years.

[8] In theory, all contaminated ground waters will eventually be restored through natural processes alone, assuming no active sources remain.

karst, or sites with poorly mapped preferential conduits, it may not be practicable to capture all contaminated flow. In other settings, flow in conduits such as solution channels may be so large as to render containment infeasible. Hence, if the plume is not static, it is important to determine if capture/containment can be achieved. If it cannot, the focus then shifts to reducing the mobility, toxicity or volume of contaminants. **[NOTE:** In older, mature plumes, plume growth may already be constrained as a result of discharge into surface waters with sufficient flow volume to dilute contaminants below detection or background levels. In this case, if access to affected ground water can be controlled, the site may qualify for management using an alternate concentration limit (ACL) approach under CERCLA**].**[9]

Mobility, Toxicity or Volume (MTV) Reduction

MTV reduction can be achieved by removing the contaminant, e.g., pump and treat or air sparging, destroying the contaminant in place, e.g., in-situ chemical oxidation, or changing the chemical to a less toxic or less mobile form, e.g., in-situ reduction of chromium VI to chromium III. Taken literally, this expectation can always be met since removal of any contaminant constitutes a reduction of mass. However, the intent of MTV reduction is to affect a meaningful improvement to the resource that ultimately translates into a reduction in risk to human health or the environment. In this context, proposals aimed at an MTV reduction RAO should be characterized in a manner that demonstrates a measurable benefit to the resource. For example, removal of mass could be shown to increase the area over which acceptable potable water concentrations can be achieved in the foreseeable future, representing a risk reduction in terms of time and location respectively, even though restoration of the entire aquifer was determined to be impracticable.

In some situations, however, demonstrating a measurable resource benefit can be more challenging. If DNAPLs are present as the source material, and mass reduction is only expected to reduce restoration time frames by a decade or two from estimated time frames that are hundreds of years long, incurring the associated costs would likely be difficult to justify. Even under these circumstances, however, it may be that mass extraction can be justified on the basis that it will significantly reduce the cost associated with other long-term remedial measures required to protect human health and the environment. For example, if a treatment wall is being installed to contain DNAPL in the area of highest concentrations (while other measures are taken to restore the lower-level concentrations of the outer, dissolved-phase plume) the cost of mass reduction within the DNAPL area may be justified based on the associated reductions in the maintenance/replacement costs of the treatment wall.

Ultimately, it will be the results from site characterization and alternative assessment activities that provide the necessary information to make informed ground water response decisions. Specific data needs should be identified through the data quality objectives process and tied directly to the objectives identified in the ground water restoration strategy.

TRANSITION AND EXIT STRATEGIES

[9] *Presumptive Response Strategy and Ex-Situ Treatment technologies for Contaminated Ground Water at CERCLA Sites*, USEPA, Office of Solid Waste and Emergency Response (OSWER) Directive 9283.1-2, October 1996.

Regardless of whether ground water restoration is ultimately determined to be practicable, an essential requirement of an optimal ground water response strategy is knowing when and how to transition from one phase of response to another. To ensure transitions between the phases proceed at the appropriate time, a transition or exit strategy must be developed and documented for each technology application/phase of the response. A transition or exit strategy may be viewed simply as *the set of information that will be used to demonstrate the desired performance has been achieved and the technology-specific objective met, such that it is appropriate to move to the next phase of the response, or terminate all activities if the desired end-state has been attained.* The four essential elements of an effective transition/exit strategy include:

1. A description of the objective of the activity, i.e., the objective associated with a technology application or phase of a response;

2. A performance "model" that describes the expected course of the remediation process, i.e., how conditions are expected to change over time from the current state until the response objective is attained;

3. A set of the performance metrics, decision criteria, and endpoints that will be used to assess how the response is progressing, demonstrate when the objective has been reached or an unacceptable condition/deviation occurs; and

4. A contingency plan that will be implemented if data indicate an objective(s) will not be met.

Defining Response Objectives

Response objectives establish the desired condition of the site once a technology application or phase of a response is complete. Response objectives may specify allowable level(s) of residual contamination in environmental media, a required level of contaminant mass reduction within media, or a required reduction in contaminant flux between media. Whatever the objective, it is critical that it be clearly stated and fully understood/agreed to before a response action is initiated. Otherwise, it will be difficult, if not impossible, to develop the performance model and metrics necessary to truly assess a technology's progress in achieving the stated objective. **[NOTE**: Although there will always be some level of uncertainty in remedy performance, project managers should clearly define what will constitute "success" and failure prior to initiating full-scale implementation of a technology. Technology application to evaluate performance should be accomplished through smaller-scale pilot studies as appropriate, i.e., full scale application should never be used to "see what happens."**]**

Performance Model

In order to develop an appropriate monitoring strategy and performance metrics, a performance model should be developed in advance to define the expected system response to the remedial technology. The Performance Model may be anything from a simple diagram to a set of numerical constructs designed to predict remedy performance and how the site will look at various times as implementation proceeds.[10] As performance assessment data are collected they are compared to the performance model to determine if the remedy is indeed performing as planned. In turn, the understanding gained from this activity is fed back into the conceptual site model (CSM) to ensure that the linkages are accurately portrayed based on any new findings.

Performance Metrics

Exit strategies must include quantitative criteria that will be used to assess response action performance, and ultimately to determine when the response has achieved its intended purpose. Without predefined metrics, any uncertainty resulting from collected data may lead to a seemingly endless (and very expensive) process of additional sampling and analysis to support a decision. The quantitative criteria established to assess performance need to specify not only where and how the criteria apply, but how they will be measured, including: sample locations, sample frequency, target parameter thresholds, duration required to demonstrate sustainability, and statistical algorithms to be used, e.g., confidence limit, type of mean, etc.[11]

Performance metrics may be defined according to interim milestones to evaluate progress, e.g., concentrations reduced by 50 percent within a specified time frame; specified mass removal rates at different times during the remediation. Alternately, monitoring criteria may be defined in terms of conditions at a specified location such as concentrations along the leading edge of a plume, or hydraulic gradients around a containment system.

The development of performance metrics should be viewed as a dynamic process that continues throughout the duration of the remedial action. In this way, performance monitoring can serve multiple purposes: to demonstrate the efficacy of remediation when the system is operating as anticipated, e.g., conditions are being met at specified points of compliance, or to allow for expedient action, e.g., technology enhancement, should performance deviate from predefined expectations. In addition, monitoring results are used to update and refine both the conceptual site model and the performance model, thus increasing confidence in our ability to predict performance over time.

Contingency Plans

A contingency plan establishes a predefined course of action should performance monitoring indicate remediation is not progressing as expected. Project managers should utilize contingency

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[10] Because some uncertainty on technology performance will always exist, a certain degree of flexibility should be allowed to periodically refine performance model expectations as data are collected and evaluated.

[11] Common statistical tests for analyzing ground water monitoring data are discussed in the DOE's *Technical Guidance for the Long-Term Monitoring of Natural Attenuation Remedies at Department of Energy Sites,* October 8, 1999.

planning to address potential deviations that would significantly impact the expected system performance. The contingency plan should not only define the criteria to signify a deviation has occurred, but also the course of action to be taken. For example, contingencies may include: 1) the collection of additional data to better assess performance; 2) re-evaluation of performance data to determine whether expectations need to be redefined; 3) implementation of an alternative remediation strategy, or, 4) re-analysis of response objectives to determine whether they are indeed attainable.

The level of analysis to identify contingencies can and should be kept relatively simple. The purpose is not to perform a "feasibility study," but rather to define acceptable and unacceptable performance/conditions, identify required data for evaluation of performance, and come up with some initial considerations of suitable contingencies.

Several generic examples of exit strategies for commonly used technologies are provided in Appendix A. A narrative example of an exist strategy for a pump and treat/MNA response is provided in Highlight 1.

Monitoring Ramp-Down Strategies

Monitoring strategies need to be dynamic and tailored to the specific circumstances and changing conditions as remediation proceeds. Monitoring is only required when there is uncertainty as to the fate and transport of contaminants or the effectiveness of the remedy(ies) implemented. As uncertainties are reduced, or the associated consequences become less significant, the need for monitoring diminishes. In other words, as data are collected and confidence in the remedy and associated performance model grows, monitoring can be "ramped-down" to conserve resources. Depending on the specific circumstances at a site, ramp-down strategies can be viewed as: 1) an intermediate step(s) in an exit strategy where eventually all monitoring will be terminated, or 2) as the final phase of an exit strategy for remedies where monitoring in perpetuity will be required.

Ramp-down strategies should include decision criteria that support the following decisions:

<u>Elimination of unnecessary analytes</u>:

- Analytes not found in initial samples and for which there is no evidence of a release;[12]
- Analytes not identified above detection limits in three successive samples; and
- Analytes detected at less than half the action level for at least three successive samples and displaying a static or downward trend.

<u>Elimination of unnecessary wells</u>:
- Wells in the interior of plumes whose boundaries are defined by other wells;[13]

[12] Some analytes may be included to monitor geochemical conditions pursuant to demonstrating conditions will support a natural attenuation approach.

[13] These wells may be needed to support performance monitoring for a monitored natural attenuation approach.

- Wells outside plumes and not deemed to be in the pathway of on-coming plumes and not required to establish background;
- Wells duplicated by proximate wells on the same isopleth; and
- Wells for which analytical data have no clear use in future decision making, e.g., consideration of when to implement a contingency.

<u>Reduction of sampling frequencies</u>:

- Sampling frequency should be selected on the basis of the slope of the observed trend lines, the degree to which empirical data match predictions, and the relative velocity of ground water. The slower the ground water moves, or the more predictable the data are, the less need there is for frequent confirmation.

COMMUNICATING GROUND WATER RESPONSE STRATEGIES

In general, for any ground water restoration strategy to be successful, it must be acceptable to the affected stakeholders. Because many remediation strategies may rely on MNA as a final phase of the response, or to address a relatively dilute portion of a contaminant plume, project managers need to be particularly cognizant of the degree to which their stakeholders are apprehensive with MNA as a remedy. As outlined in the DOE's MNA decision maker's framework guide, the rationale for the strategy must be well documented and effectively communicated.[14] Two critical elements in effective communication of ground water response strategies include: 1) a realistic comparison of alternatives with respect to cost and risk reduction achieved; and, 2) the explicit identification of uncertainties and the means by which they will be managed.

<u>Alternative Comparison</u>

It is essential to *accurately and objectively characterize alternatives and present their respective costs and degrees of effectiveness clearly* to stakeholders. Each remedy must be assigned an expected performance profile that reflects the anticipated reductions in contaminant concentrations over time so that differences in cost can be compared with differences in risk reduction being achieved. **[NOTE:** In some respects, it can be argued that the difference in the time required to achieve actual restoration is the most important consideration. Until concentrations are reduced below specified use criteria, e.g., MCLs for drinking water, protection will be provided through the use of access restrictions, not differences in the approaches to mass reduction**]**.

It also is important that *proposed remedies be assigned realistic projections on their likely effectiveness*. Often, there is a default assumption that a proposed remedy will be effective without sufficiently evaluating past experience or fully considering the potential effects of site uncertainties on a technology's performance. Without objective estimates of a technology's expected effectiveness, remedies of little or no value to the resource may be implemented because of the assumption that action of some kind must be beneficial, when in fact, the opposite

[14] *Decision-Making Framework Guide for the Evaluation and Selection of Monitored Natural Attenuation Remedies at Department of Energy Sites*. May 13, 1999.

may be true.[15] Only when the life-cycle cost and associated resource benefit/risk reduction of the individual response options being considered are objectively compared and clearly communicated, will stakeholders be able to make informed decisions as to the acceptability of whatever measures are being proposed.

Uncertainty Management

It is virtually impossible to eliminate all the uncertainty associated with environmental restoration prior to selection of a remedy. As a consequence, there will always be a need to manage uncertainties through contingency planning.[16] For the most part, the significant uncertainties associated with restoration of ground water are those related to whether the remedy will be effective, which in large part is a result of uncertainties in those site conditions that can affect technology performance. However, despite these uncertainties, protectiveness can be assured if an appropriate monitoring program is designed and implemented that will provide ample warning of an unacceptable condition(s) and a contingency plan is in place that will mitigate any adverse impacts before unacceptable exposures occur (see Table 1). Demonstrating that an effective monitoring program is in place and a commitment to respond rapidly with a predefined contingency plan should help alleviate many of the concerns stakeholders have when confronted with response uncertainties. The biggest mistake that can be made in communicating response strategies to stakeholders is to characterize the expected outcome of a response as a certainty when in fact, experience has shown that such certainty is rarely if ever justified.

[15] In some circumstances, active remedies can trigger unintentional movement of the contaminants themselves or work to negate the effects of natural attenuation mechanisms, e.g., pump and treat system lowers water table and promotes aeration, thus reversing the anaerobic mechanisms that otherwise might be effectively degrading chlorinated solvents.

[16] Uncertainty Management: Expediting Cleanup through Contingency Planning (DOE/EPA, February, 1997).

Highlight 1

Example Exit Strategy for a Pump-and Treat/ Monitored Natural Attenuation Remedy

I. Background/Description of Remedy

Pursuant to the Record of Decision (ROD) for Operable Unit 2, a pump-and-treat system is being installed to remediate a trichloroethylene (TCE) plume approximately 300 feet long and 250 feet across, and spanning the entire 30 foot thickness of the surficial aquifer underlying the site. The plume consists of ground water contaminated at 3 ppm TCE at its most concentrated point, with the perimeter defined by the contours of the 5 ppb isopleth. Low levels of 1,2, dichloroethylene and vinyl chloride have also been observed. A private, off-site domestic well downgradient of the plume is the only potential exposure pathway of concern, however, there has been no detection of contamination in this well. Ground water will be pumped at a rate of 5 gallons per minute utilizing a single centrally located extraction well and run through an above-ground air stripping unit prior to discharge to a local industrial sewer. [Note that HRC and ISCO were also evaluated as potential response alternatives during the feasibility study, but were determined to be less cost-effective than pump and treat, given the estimated strength of the residual source following excavation of the solvent tank.] Ground water use restrictions are in place to ensure no potable access wells are installed in the affected area. The evaluation of site conditions relative to the monitored natural attenuation (MNA) protocol developed for this site (see Appendix#) indicates that once concentrations are reduced to 20 ppb, the plume will be static and continued use of the pump-and treat-system would not be cost-effective, i.e., the cost per unit of contaminant extracted increases significantly with little reduction in restoration time frame over what is expected to occur naturally. Therefore once the 20ppb level has been attained, the remedy will transition to MNA.

II. Pump and Treat Transition Strategy to MNA

a. <u>Remedial Action Objectives</u>

The remedial action objectives for this phase of the response are to: 1) prevent expansion of the extant plume; and 2) remove sufficient mass to achieve an average concentration across the plume of 20 ppb.

b. <u>Performance Assessment Model</u>

It is expected that once activated, the extraction well will create a drawdown cone extending approximately 20 feet beyond the current 5 ppb isopleth, and this capture zone will require no more than 75 hours to establish and will be maintained throughout operation of the remedy. It is also expected that the 5 ppb isopleth will retreat toward the extraction well and no detectable level of volatile organic compounds will be observed in monitoring wells outside the capture zone. Based on the results of numeric modeling, it is estimated that concentrations of TCE will decline in a first order decay fashion with an assumed half life of twenty-two months. Hence, it is predicted that the target concentration for transition to the MNA phase of 20 ppb will be reached after 7 years of operation.

c. <u>Performance Measures (Monitoring)</u>

TCE concentrations will be monitored using three "performance" wells located within the current plume, two "sentinel" wells downgradient of the leading edge of the plume and upgradient of the offsite domestic well in the plume trajectory, and one "ambient" well upgradient of the plume to track background conditions.

All six monitoring wells initially will be sampled on a quarterly basis with frequency subject to modification pending evaluation of results against performance expectations and the decision criteria outlined below. Each monitoring well will be sampled for volatile organic compounds (with emphasis on TCE, cis and trans 1,2 dichloroethlyene, 1,1 dichloroethylene, and vinyl chloride). Water levels will be measured with each sample, and the potentiometric surface will be plotted after each sampling event. The capture zone, as indicated by the observed potentiometric surface, will be compared to the plume boundaries as defined by the 5 ppb isopleth.

d. <u>Performance Assessment, Decision Criteria and Contingencies</u>

Potentiometric surface data will be plotted against the known extent of the plume to determine whether hydraulic control has been attained. If the plume (as defined by the 5ppb isopleth) is found to extend beyond the capture zone, an additional extraction well will be installed in the area of deficiency.

Contaminant concentrations will be plotted over time for each monitoring well. Should contaminants be observed in downgradient detection wells, an assessment will be conducted to determine whether capture was incomplete because of a loss of a portion of the downgradient edge of the plume during remedy installation, or because of insufficient connectivity across the breadth of the plume. In the former case, the condition would be temporary and a cost-effectiveness evaluation will be made to determine whether: 1) a temporary alternate water supply should be provided until the detached lobe of contamination attenuates; or 2) an additional extraction well should be installed to capture the contamination. Should insufficient connectivity occur, additional extraction wells may be effective in achieving the desired capture, unless the inability to capture the plume arises from preferential conduits. The later would be indicated if performance wells are consistent with the performance model but sentinel or receptor well data are not. As discussed in the ROD, the impracticability of finding and capturing preferential conduits will serve as the basis for the use of well-head treatment as the contingency in the event that preferential conduits are present.

If a downward trend is observed in the three wells within the plume after four years of monitoring, with an observed half life on the order of twenty-four months or less, the conclusion will be the remedy is performing according to expectations and monitoring will be reduced to a biannual basis for the next two years and annually thereafter. If a downward trend is observed, but at a half life that is longer than anticipated, monitoring will continue on a quarterly basis, and performance expectations revised accordingly. Once a minimum of four quarters of data are collected that match performance expectations (original or revised), monitoring frequency will be reduced to biannual monitoring for a period of one estimated half life, and annually thereafter.

If data indicate no downward trend, the ability of the residual source term to maintain static concentrations is greater than estimated, and in-situ oxidation or hydrogen release compounds will be reconsidered as means of reducing the source term further and shortening the estimated time for restoration.

III. Exit Strategy for Monitored Natural Attenuation

a. <u>Remedial Action Objectives</u>

To restore the effected ground water to its highest beneficial use as a drinking water source, i.e., to less than 5 ppb TCE.

b. Performance Assessment Model

Based on the results of numeric modeling, it is estimated that natural attenuation mechanisms (specifically, co-metabolism degradation and dilution/dispersion) will cause reduction of concentrations of TCE in a first order decay fashion with an assumed half life of 30 months. Based on this assumed rate of decay, it is predicted that the target concentration of 5 ppb will be reached after 5 years of monitoring. An initial rise, followed by similar first order decay curves for the primary degradates, is expected. Reduced, anaerobic conditions are assumed to prevail in the zone of degradation.

c. Performance Measures (Monitoring)

Monitoring will consist of: 1) two sentinel wells “downgradient” of the leading edge of the plume and upgradient of the one known receptor well in the plume trajectory; 2) three “performance” wells located within the current plume; and, 3) one “ambient” well located upgradient of the plume to monitor background conditions (see figure 1).

Once the pump and treat system is shut down and the transition to MNA begins, the sampling frequency for all six monitoring wells will return to a quarterly basis initially, with frequency subject to subsequent modification pending evaluation of the results to performance expectations. Each monitoring well will be sampled for volatile organic compounds (with emphasis on TCE, cis and trans 1,2 dichloroethlyene, 1,1 dichloroethylene, and vinyl chloride) as well as parameters associated with the MNA protocol such as dissolved oxygen, oxidation- reduction potential, and pH.

d. Performance Assessment, Decision Criteria and Contingencies

Contaminant concentrations will be plotted over time for each monitoring well. Should contaminants be detected in the downgradient, sentinel wells, the pump and treat system will be restarted and an alternate water supply made available if requested by downgradient landowner.

If data indicate an increase in contaminant concentrations, i.e., rebound has occurred, the pump and treat system will be restarted and continued until concentrations again are below the 20 ppb threshold for transition to MNA.

If a downward trend (in accordance with the assumed half-life decay rate of 30 months or less) is observed in the three performance wells within the plume after four years of monitoring, the conclusion will be the remedy is performing according to expectations and monitoring will be reduced to a biannual basis for the next two years and annually thereafter, until data indicate that the average concentration across the plume meet the target concentrations of 5 ppb for eight successive quarters. If a downward trend is observed, but at a half life that is longer than anticipated, monitoring will continue on a quarterly basis, and either: 1) the performance expectations will be revised accordingly, or 2) mass removal will be initiated to bring the predicted period of performance to a value within the acceptable time frame. Once a minimum of four quarters of data are collected that match performance expectations, monitoring frequency will be reduced to biannual monitoring for a period of one estimated half life, and annually thereafter, until data indicate that the average concentration across the plume meets the target concentrations of 5 ppb for two successive years.

Table 1
Uncertainty Matrix - Monitored Natural Attenuation Response Design

Response	Parameter	Design Basis (Assumed Conditions)	Potential Range of Conditions	Impact of Deviation	Threshold for Impact (Probability)	Monitoring	Contingency	Time to Implement
Monitored Natural Attenuation	Long-term geochemical stability	Stable	Stable/ Unstable	Arsenic becomes mobile	ph > 8 ph < -3 (low)	Eh-ph, As in sentinel wells	Pump and treat	6 months
	Irreversibility of adsorption	Irreversible	Reversible/ Irreversible	Future release of arsenic	> 10% release (low)	As in sentinel wells	Pump and treat	6 months
	Presence of preferential pathways	None	None/ Several	Arsenic transported to receptor well	> 10% of flow (moderate)	Monitor receptor wells for As	Wellhead treatment	3 months
	Current perimeter is static	Static	Retreating/ Growing	No immediate risk concern due to buffer zone	Flux exceeds buffer zone > 1/4 mile growth (moderate)	As in sentinel wells	Pump and treat	6 months
	Permanence of institutional controls	Non-residential	Non-residential/ Residential	Create potential for ground water use/ ingestion	First potable well (low)	Five-year reviews	Buy out water rights	1 month

Appendix A: Examples of Exit Strategies for Commonly Used Technologies*

A-1: Example Elements of an Exit Strategy for In-Situ Chemical Oxidation

Description of Remedy: *In-situ chemical oxidation is applied as a source control measure in the head of the plume where DNAPL has been observed.*

Remedial Action Objectives: *Remove sufficient mass of DNAPL for transition to containment (pump and treat) and ultimately restoration (MNA) of the dissolved phase portion of the plume.*

Performance Assessment Model Parameters (P)	Performance Metrics (PM); Decision Criteria (DC)	Potential Deviation from Performance Model and Impacts	Contingencies
P 1: Oxidizing solution is injected from a bank of wells and drawn to a second bank of extraction wells in a manner that sweeps the targeted area of the plume.	**PM 1:** Take piezometric readings to map resultant flow patters with respect to the target zone. **DC 1:** Flow lines indicate loss of greater than 10% of injected fluids and/or failure to contact greater than 95% of the targeted source area.	Presence of preferential conduits or regional gradients prevent injected solution from contacting all of the targeted area and/or result in loss of portions of the injected reagents.	Modify well locations to achieve desired coverage.
P 2: Oxidizing solution is injected in sufficient concentration and volume to meet the oxidation demand of the DNAPL and the matrix in which it is found. Retrieved fluids will contain high levels of contaminant and little or no residual oxidizing agent until demand has been satisfied.	**PM 2:** Monitor extracted ground water for oxidation state and contaminant. **DC 2:** Concentrations of contaminant are above target levels and oxidizing solution strength is greater than 90% of its expected strength (Note: expected strength accounts for dispersion and dilution between point of injection and point of extraction and is determined by modeling injection under an assumption of no reaction or adsorption.	Geochemistry is such that oxidizing agent is not capable of degrading the target species and/or their degradates.	Change reagents or reagent strength; Apply an alternate technology (e.g., six-phase heating).
P3: Oxidizing agent is transported at a retarded velocity, and will arrive at a predictable breakthrough front.	**PM 3:** Monitor extraction wells and intermediate points for arrival of breakthrough front (i.e., a rapid increase in concentrations). **DC 3:** Transport times are more than twice those predicted.	Loss of injected fluids at some location(s) within the target area, or There is a much higher matrix demand than anticipated.	Apply an alternate technology; or Increase concentration of reagent.
P4: Precipitation of oxidation byproducts does not lead to unacceptable decline in matrix permeability.	**PM 4:** Monitor required injection pressure and flow rates and extraction rates. **DC 4:** Permeability loss approaches point where oxidizing fluid cannot be distributed across target area.	Permeability loss is greater than anticipated resulting in an inability to effectively treat the target area.	Change reagents.

Endpoint: Oxidizing solution at 90% of expected strength in extraction well.

A-2: Example Elements of an Exit Strategy for a Permeable Treatment Wall			
Description of Remedy: *Permeable Treatment Wall applied in the mass removal/containment phase of the ground water strategy; placed within the leading edge of the plume following removal of source term (drummed solvents and highly contaminated soils).*			
Remedial Action Objectives: *To remove sufficient contaminant mass from the plume such that concentrations downgradient of the wall remain below target levels, while concentrations in excess of target levels are contained to the area upgradient of the wall.*			
Performance Assessment Model Parameters (P)	**Performance Metrics (PM); Decision Criteria (DC)**	**Potential Deviation from Performance Model and Impacts**	**Contingencies**
P 1: Under reducing conditions, zero valent iron causes rapid dechlorination of solvent molecules, resulting in contaminant concentrations below target levels in the water within and down gradient of the wall.	**PM 1:** Samples of interstitial waters taken from midpoint within the wall are analyzed for oxidation reduction (redox) potential, pH, and Oxygen. Samples taken upgradient analyzed for contaminant concentrations. Samples taken within and downgradient of the wall analyzed for contaminant concentrations and breakdown products. **DC 1:** Redox level is at or below threshold for dechlorination; contaminant concentration levels are less than or equal to half the difference between influent and target concentrations.	The width of the wall or the presence of preferential conduits within the wall lead to insufficient contact time and, therefore, insufficient dechlorination.	Homogenize the media or replace wall with a pump-and-treat system. Replace or augment the media in the wall to increase percent of iron.
P 2: Although permeability of the wall will decrease over time as evidenced by a gradual increase in head, the wall will remain sufficiently permeable.	**PM 2:** The head across the wall is measured with piezometers upgradient, in, and downgradient of the wall. **DC 2:** Head increase exceeds threshold calculated to push plume around or under the wall.	Chemical precipitation of hydrous oxides or biofouling rates exceed expectations, resulting in reduced period of performance.	Rehabilitate the wall by ultrasonic or surge methods to dislodge particulates, replace the media, or replace with pump and treat.
P 3: Entire plume will be treated within *x* years (based on natural flushing time for the head of the plume).	**PM 3:** Recalibration of performance model based on extrapolation of temporal trends from upgradient monitoring data. **DC 3:** Predicted number of years required to treat plume exceeds “reasonable timeframe” threshold established to coincide with expected date of property transfer.	Flushing rate is much slower than predicted.	Augment wall with a pump-and- treat system, or utilize in-situ chemical oxidation to reduce mass.
P 4: Entire plume flows through the wall and is treated; therefore, concentrations at either end of the wall or downgradient of the wall never exceed target levels.	**PM 4:** Samples from wells at either end, underneath, and downgradient of the wall are analyzed for contaminant concentrations. **DC 4:** Concentration in wells lateral to ends of wall or downgradient of wall exceed target levels for two or more quarters.	Plume width or depth exceeds the wall’s capture capacity.	Extend the wall or replace with pump and treat.
Endpoint: Concentrations upgradient and downgradient of the wall are below target values as defined by statistical representation across the area of the former plume.			

A-3: Example Elements of an Exit Strategy for a Pump-and-Treat System (including recirculating well designs)			
Description of Remedy: *Pump-and-Treat system applied in a mass removal/containment mode that encompasses all portions of the plume above target concentrations. System installed after or in conjunction with removal of the source term (drummed solvents and highly contaminated soils).*			
Remedial Action Objectives: *Plume containment and removal of sufficient mass to achieve an average concentration across the plume that supports transition to monitored natural attenuation.*			
Performance Assessment Model Parameters (P)	**Performance Metrics (PM); Decision Criteria (DC)**	**Potential Deviation from Performance Model and Impacts**	**Contingencies**
P 1: Pump and treat system will retrieve all water contaminated above target concentration levels.	**PM 1:** Samples from downgradient monitoring wells analyzed for contaminants of concern and degradates. **DC 1:** Concentrations greater than health-based standards downgradient of the capture zone.	Capture is incomplete leading to concentrations in excess of health based standards downgradient of the capture zone.	Augment the system with additional extraction wells, or increase extraction rate.
P 2: Radius of influence of the capture wells is sufficient to cover all targeted portions of the plume.	**PM 2:** Potentiometric surface measured across all targeted portions of the plume to determine resultant flow pattern during pumping. **DC 2:** Targeted portions of the plume do not flow to extraction wells.	Unable to establish sufficient radius of influence.	Augment the system with additional extraction wells, or increase extraction rate.
P 3: Continued desorption and flushing of the matrix causes exponential decline in concentrations to target levels within *X* years.	**PM 3:** Trend projections based on contaminant concentrations monitored within the plume. **DC 3:** Trend indicates concentrations will exceed target levels beyond *X* years.	Residual source term has greater strength than assumed.	Apply additional source control measures (in-situ chemical oxidation or hydrogen release compounds) or evaluate feasibility of extending the life of the pump-and-treat system.
P 4: Connectivity is such that there are no preferential conduits that cannot be effectively controlled	**PM 4:** Samples from downgradient monitoring well and receptor well analyzed for contaminants of concern and degradates. **DC 4:** Contaminants detected in downgradient well in excess of health-base standards despite apparent capture in the performance wells.	Preferential pathways exist which cannot be effectively captured.	Install wellhead treatment or provide alternate water supply if migration to receptor well is possible or expected.

A-4: Example Elements of an Exit Strategy for Monitored Natural Attenuation			
Description of Remedy: *Monitored natural attenuation (MNA) applied as the final phase of a ground water strategy after mass removal has eliminated active sources and stabilized the plume.*			
Remedial Action Objectives: *To restore ground water concentrations to levels required for highest beneficial use or a drinking water source.*			
Performance Assessment Model Parameters (P)	**Performance Metrics (PM); Decision Criteria (DC)**	**Potential Deviation from Performance Model and Impacts**	**Contingencies**
P 1: Biodegradation and dispersion/dilution continue to reduce concentration of contaminants at a rate that will achieve target levels within an agreed upon timeframe.	**PM 1:** Samples from "performance wells" throughout the plume analyzed for contaminants of concern to determine concentration trends. **DC 1:** Extrapolation of concentration trends do not achieve remedial action objective in acceptable timeframe.	Attenuation mechanisms are occurring at slower rates than anticipated.	Revise performance assessment model. If extended timeframe considered unacceptable, evaluate, and if feasible, affect mass removal to further deplete source inventory.
P 2: Boundary of the plume, as defined by the target concentration isopleth is static or retreating.	**PM 2:** Samples from downgradient (e.g., sentinel) wells analyzed for contaminant concentrations. **DC 2:** Presence of contaminants/exceedance of health-based standard in sentinel well.	Plume continues to grow or migrate.	Initiate pump and treat to contain the plume until plume stasis is again believed to have occurred.
Endpoint: Concentrations meet target levels for highest beneficial use for a period of 8 sequential quarters as measured in monitoring well network.			

* As discussed in the guidance, exit strategies should include not only quantitative criteria to assess performance, but also how they will be measured and the statistical algorithms to be used. The four generic examples in this Appendix have been included to simply help readers conceptualize how the various elements of an exit strategy might be portrayed. Therefore, numeric threshold values or specific statistical approaches have not been incorporated fully as would be appropriate when developing a project-specific exit strategy.